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Research highlights

- ✓ High yielding maize-based cropping systems can be managed to limit their impact on soil and water quality
- ✓ The harvest of the entire plant, straw included reduces N leaching by 10-20%, but carbon sequestration is also reduced
- ✓ A maize-Italian ryegrass double cropping system improves the efficiency of organic fertilizers, and reduces leaching by 25-40% relative to monoculture
- ✓ A rotation with grass ley reduces N impact relative to monoculture only when fertilized with urea
- ✓ Urea, slurry, and farmyard manure are equally utilized by maize; when well managed, both organic fertilizers build up the SOM content and reduce N leaching by 20-50%.

Abstract

Maize (*Zea mays*, L.) is not only the main crop in the intensively-cultivated Po Plain (Northern Italy), but also the one that produces the largest N surplus. This study is based on experimental data from the Tetto Frati long-term trial (Turin, NW Italy) to demonstrate that the impact on soil and water quality of high-yielding, maize-based cropping systems can be reduced through proper management.

Nitrogen use efficiency and loss indicators were calculated and compared among various management options: (i) maize monoculture at high N fertilizer rates for grain production (most widespread management), (ii) entire plant (with straw) harvest, (iii) double-cropping system with a winter crop, (iv) maize - grass ley rotation, and (v) change in fertilizer type.

The entire maize plant removal reduced N leaching by 10-20%; however, carbon sequestration was also reduced. A maize-Italian ryegrass double cropping system improved the efficiency of organic fertilizers, and reduced leaching by 25-40% relative to monoculture. A rotation with grass ley reduced N impact only when fertilized with urea, and not when organic fertilizers were used. Urea, slurry, and farmyard manure were equally utilized by the crop; if distributed and incorporated just before sowing, both organic fertilizers built up the soil organic matter content and reduced N leaching by 20-50% with respect to urea. This study has shown that farmers in NW Italy have several opportunities to continue cultivate maize thus accomplishing agri-environmental legislation.

Keywords

Maize; N leaching; indicators; slurry; farmyard manure; N use efficiency

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1. Introduction

Maize (*Zea mays*, L.) is one of the most diffuse crops throughout the world (Leff et al., 2004), as it adapts to very different climatic and management conditions (e.g. Chang and Janzen, 1996; Chikowo et al., 2004; Kristiansen, 2005; Schröder et al., 2005; Zhen et al., 2006; Payet et al., 2009). It is also one of the most versatile of crops—whether as a grain or whole crop. Maize grain is used for both human and animal consumption as well as for industrial or energy purposes. The whole plant can serve as forage or biomass for biogas production or its straw can be chopped and incorporated into the soil, or harvested to function as livestock bedding.

Maize has endured a number of criticisms. Frequently accused of being a crop that wastes water because it is usually irrigated, it actually has been shown to convert water to biomass more efficiently than many alternative crops (see Katerji et al., 2008 for a literature review of water use efficiency coefficients, and Grignani et al., 2009 for an analysis of crop irrigation requirements in Northern Italy). Similarly, maize was often tagged as the crop that puts environmental quality at a greater risk than others, following Pimentel's work (1996) and the long series of trials that focused on the environmental and economic effects of agricultural practices associated with high N losses (Kramer et al., 2002). In fact, in a warm and water-available climate, maize is a most efficient user of these inputs. Since only rarely is a productivity decrease due to excess resources, farmers allocate most of their fertilizer, irrigation water, and energy resources to maize.

Maize is the main crop in the fertile Po Plain (Northern Italy), which is the largest and most intensive agricultural area in Italy, as it hosts 36% of the Utilized Agricultural Area (UAA) and 75% of the livestock (ISTAT, 2000). Maize is cultivated on as much as 23% of the UAA for grain production (ISTAT, 2000; Autorità di Bacino del Fiume Po, 2006). In the Northern Italy climate, the plant reaches physiological maturity at the end of summer; thereafter, the grain continues the drying process. Since it never attains a humidity level that is needed for conservation, it requires drying post-harvest by an external heat source. Its straw is normally chopped and incorporated into the soil or harvested to serve as livestock bedding. Alternatively, the entire maize plant is frequently harvested prior to its physiological maturity, chopped, and then ensiled as ruminant forage. Other uses of maize are not common in Northern Italy. Local regulations (e.g. Regione Piemonte, 2009) promote the use of winter catch crops as maize leaves the soil bare during winter. The most diffuse winter cover used in the region is, in fact, a secondary crop of Italian ryegrass (*Lolium multiflorum*, Lam.) that is harvested in May when maize is late-sown.

The large amounts of slurry or farmyard manure that are produced across the territory make organic fertilizers largely available to any crop, but especially to maize, which is the typical crop of pig, beef, and dairy farms. According to common practice, N fertilizer is partly distributed in spring just before sowing in the form of slurry or manure, and partly top-dressed at ridging as mineral fertilizer (Bassanino et al., 2007; 2011). This management complies with local implementations (D.M. 7 April 2006) of the Nitrates Directive (Anonymous, 1991) and the Water Framework Directive (Anonymous, 2000). No singular agreement exists on how best to reduce the use of N sources across Europe; therefore, every country or region (as in Italy) has its own legislation. The logic behind this choice is that European Union-wide objectives, such as those to protect water resources, can be optimized best through area-specific efforts.

Scientific data may help identify management solutions that can be accepted by farmers and meet environmental targets. A deep knowledge of the possibilities, constraints, and practices of local farms is essential in order to propose viable alternative practices (Grignani e Zavattaro, 2000; Zhen et al., 2006; Ju et al., 2007; Bassanino et al. 2011). Although comparisons of single agronomic factors or of management packages can be found in the literature (e.g. Borin et al., 1997; Grignani and Zavattaro, 2000; Grignani and Laidlow, 2002; Sacco et al., 2003a; Morari et al., 2011, Perego et al., 2011), few experimental trials have been designed to evaluate the sustainability of a range of management options spanning medium and long term experiments (Nel et al., 1996; Yamoah et al., 1998; Denison et al., 2004).

This paper considers how to reduce the N impact of intensively-cultivated maize in the Western Po Plain. Our aim is to evaluate the following fertilisation management options available to the region's local livestock farmers: (i) total plant harvest, (iii) double cropping system with a winter catch crop, (iii) grass ley rotation with the maize, and (iv) fertilizer type change. All tested cropping systems are viable options for local livestock farms. We test the hypothesis that maize, if well managed, may exert a limited environmental impact on the soil and water quality, maintain high yields, and efficiently recycle large amounts of manures, utilizing data from the long-term platform of Tetto Frati of the University of Turin. Only nitrogen is considered; other nutrients and water issues are outside the scope of this evaluation. Same site and related studies can be found by Borda et al. (2011) who evaluated phosphorous and Bertora et al. (2009) who first presented a greenhouse gas emission analysis.

2. Materials and Methods

We report and discuss data from the long-term platform of Tetto Frati at the Experimental Centre of the University of Turin during 1993-2006. Grignani et al. (2007) and Bertora et al. (2009) have previously described the soil, site, and treatments; relevant points of those reports will be presented hereafter.

The trial site lies on deep, coarse, calcareous, free-draining soil (see also Lo Russo et al., 2003). The texture is loam. The initial soil N content was 1.14 mg kg^{-1} with a C:N ratio of 8.6. Its temperate, sub-continental climate is characterized by two main rainy periods that occur during spring (April and May) and autumn (September-November). Total average annual precipitation is 750 mm. Since 1992, the experiment (a randomized block design with three replicates) has compared, at plot scale, 38 different combinations of maize-based cropping systems and fertilization managements. To ensure representative results, typical farm machines and agronomic techniques were adopted.

Our analysis considered the following cropping systems: (i) maize for grain production (Mg); (ii) maize for silage (Ms); (iii) double annual crop rotation with Italian ryegrass in autumn and winter, and maize for silage in spring and summer (Mr); and (iv) grass ley rotation with maize for silage (Ml) in which the first ley phase spanned 1992-1994 and the second ley phase spanned 1998-2001, for a total of six years in the monitored period. These cropping systems were then overlaid with several fertilization managements: (i) urea at four levels (U100, U200, U300, and U400), (ii) bovine slurry (S) at two levels (Low and High), (iii) composted farmyard manure (F) at two levels (Low and High), plus a control (0N). Across the experimental duration, supplied organic fertilizer amounts were kept constant while N varied according to the varied nutrient concentration associated with manures.

Table 1 reports the average amount of total-N supplied to each cropping system. For slurry and manure, the average dry matter content was 5.7 and 25.7%, respectively. Maize mineral and organic fertilizer mechanics included distribution to the soil surface and incorporated within one day; sowing followed soon after. All fertilized treatments were top-dressed with a fixed amount of 100 kg ha^{-1} of urea-N, distributed and incorporated by ridging at the maize jointing stage. For leys, fertilizers were distributed to the soil surface during March at growth resumption and during May after the first cut. To eliminate any phosphorous (P) or potassium (K) direct or interactive effect on N results, P and K were over-supplemented with simple mineral products (superphosphate and potassium chloride).

2.1. Crop management

Both grain and silage maize underwent the same crop management and used the same hybrid. Sowing occurred during mid-April to mid-May in the Ms, Mg, and Ml systems, and in late May in the Mr system (after the Italian ryegrass harvest and tilling with a spading machine). Maize was treated with chemical weed control and sprinkle irrigation in which the N content was measured as negligible (less than 3 mg $l^{-1}$of N). Silage maize was harvested in early September (physiological maturity) while grain maize was harvested from late September to early October. The maize residues in the Mg treatments were chopped in November or December and then incorporated into the soil with a rotavator.

Italian ryegrass (*Lolium multiflorum*, Lam.) was sown in the Mr system soon after the silage maize harvest (early October). Its seedbed was prepared using a rotavator. The crop was harvested during mid- to late May, the grass sods were destroyed using a spading machine and a rotavator, and maize was then sown.

Cocksfoot grass (*Dactylis glomerata*, L.) was used in the first ley cycle and tall fescue (*Festuca arundinacea*, Schreb.) in the second cycle. White clover (*Trifolium repens*, L.) naturally developed in the control plots but was absent in those fertilized. The sward was sown in September (1992 and 1997) after basic fertilization and soil tillage by spading machine, rotavator, and disk harrow. Three or four cuts were performed each year during the heading stage. Ley irrigation was like that done for maize, and a spading machine and rotavator destroyed the grass sods in autumn 1994 and 2001.

2.2. Measurements

The N supplied to the plots was calculated from the amount of fertilizer distributed and the nutrient concentration of the fertilizer. We assessed the aboveground crop biomass production by sampling an 18 m^2 area for maize, and 10 m^2 for both Italian ryegrass and leys; its production was expressed as oven-dried matter (DM). In the case of crop nutrient uptake, it was determined from analyzed N concentrations in plant harvest samples. Both measures were determined annually.

Our initial measurements of soil organic matter (SOM) and total N content (spring 1993) were from a pooled sample; but for those done in 1999, 2003, and 2007 (at monitoring period ends) we used plot-specific sampling. Data reported here refer only to the 0-30 cm horizon in 1993 and 2007. Grignani et al. (2007) and Bertora et al. (2009) reported results for intermediate sampling dates.

Soil mineral N (ammonium + nitrate) concentration as extracted by KCl was monitored to a depth varying from 50 to 100 cm, with two replicates, in a series of treatments at various sampling dates in two campaigns—one from August 1993 to April 1996 and the other from April 2002 to June 2003. The methodology used is identical to that described by Alluvione et al. (2010) with two exceptions—the KCl extracting solution was 0.5N and the soil to solution ratio was 1:3. Only the nitrate-N fraction from the 0-50 cm deep layer is reported in this paper.

The mineral N (ammonium + nitrate) soil solution concentration at 100 cm depth as extracted by porous cups was monitored for some of the treatments at various sampling dates (two replicates each), according to the method described by Grignani and Zavattaro (2000). Sampling campaigns were the same as the soil extraction measurements noted above. We report only nitrate-N data here.

2.3. Statistical analysis

The dry-matter production, N uptake, and soil N content were interpreted through an analysis of variance (ANOVA). The cropping system, fertilization management, block and the interaction between the cropping system and fertilization management were considered as fixed factors. The between-year variability was included in the error. The mean separation for the main effects and interactions were obtained using S-N-K test (Townend, 2002). Effects were considered significant for $P \leq 0.05$.

2.4. Indicators of N use efficiency and impact

The following indicators of the N use efficiency and the impact of cropping systems were calculated:

- R/F, or removal to fertilizer ratio, was calculated as the amount of N removed as yield (*Nremoval*) divided by the total amount of fertilizer N (*Nfertilizer*);
- AR, or Apparent Recovery, was calculated as:

$$AR = \frac{Nremoval - Nremoval_{0N}}{Nfertilizer}$$

where $Nremoval_{0N}$ is the amount of N removed by the control. Given the external N sources in the control (N_2-fixation), AR values of Ml were calculated using the Ms control plot;

- Surplus was calculated as

$$Surplus = Nfertilizer - Nremoval + Ndeposition$$

which corresponds to a Soil Surface Balance (SSB) following the IRENA methodology (COM, 2000). It was expressed in kg ha^{-1} yr^{-1} of N. Unlike Oenema et al. (2003), the amount of N from fertilizer was not reduced by NH_3 volatilization. Nitrogen in rainfall was set to 26 kg ha^{-1} yr^{-1}, according to site observation and consistent with the territorial study reported by Bassanino et al. (2010);

- SSyB, or Soil System Balance, was calculated as:

$$SSyB = Nfertilizer - Nremoval + Ndeposition - \left(SoilN_{final} - SoilN_{initial}\right) - Nvolatilization$$

where *SoilN* was the N content of the 0-30 cm layer of the soil, *Nvolatilization* was the amount of N volatilized as NH_3, and all the other terms of the equation have the same meaning as described above. The measured soil N content in 2007 and 1993 were used as "*final*" and "*initial*" value; their difference was divided by 14 to equate to a single year. In slurried and manured treatments the NH_3-N volatilization was estimated using the MANNER method (DEFRA, 2004), using experimental weather and management data. It ranged between 4.1% and 9.1% of total supplied N. In plots treated with urea, a fixed volatilization coefficient of 5.6% of supplied N was used according to Dinuccio et al. (2007). The SSyB was expressed in kg ha^{-1} yr^{-1} of N. This indicator considers that what is missing in the mass balance was lost as denitrification or leaching below the considered depth (Oenema et al., 2003).

As the amounts of N supplied differed among cropping systems, yield and N removal data were standardized to a reference value of 270 kg ha^{-1} of N. The standardization was made by linear interpolation between Low and High slurry and farmyard manure, or U200 and U300 treatments. Indicators were then calculated on interpolated values.

The efficiency of N from organic fertilizers was also expressed as the percentage of N that was made available to the crop. If we assume that the available N is estimated from the amount of N in the yield (*Nremoval*), and that the crop can fully utilize N from mineral fertilizers and atmospheric deposition, but only a fraction of organic fertilizers, then we obtain:

$$Nremoval = Mineral\text{-}N + Organic\text{-}N \times Ko + Ndeposition$$

where *Mineral-N* and *Organic-N* are the N amounts supplied as mineral and organic fertilizers, and *Ko* is the percentage of *Organic-N* that was made available to the crop through mineralization.

Unlike most other crops, there is a large difference between total and marketable yield N uptake in maize when only grain is harvested. Therefore, AR and Ko values for Mg are not directly comparable with those of the other systems here analyzed.

2.5. Leached N

Model simulations provided estimates of the amounts of N leached over the study period. The simulation model Daisy ver. 4.01 (Abrahamsen and Hansen, 2000) was used. It was parameterized using measured data of soil hydrology, crop, management, and climate data from this trial. More detailed data on crop growth, Leaf Area Index, plant partitioning, N concentration in plant tissues, and root weight measured in a companion long term trial (Sacco et al., 2003b; Desogus et al., 2008) were used to parameterize the maize crop. Model predictions were compared with measured crop biomass (14 years), N uptake (14 years), soil water content (18-94 sampling dates at three depths, depending on the treatment), soil mineral N content (same as soil water content), soil C, and N contents (three sampling dates at three depths) to calibrate the soil organic matter turnover compartment of the model across 11 reference treatments. Monaco et al. (2010a) has reported the preliminary results for model performance. The crop N uptake Relative Root Mean Square Error (RRMSE) was 21.1%, and the Mean Difference (MD) was -21 kg ha^{-1} yr^{-1}, while the soil total N content RRMSE and MD were 6.3% and -0.3 t ha^{-1}, respectively.

In this paper, the model was used to predict N leached in treatments at the reference value of 270 kg ha^{-1} of N fertilization. Results presented here are the average of the simulated 1993-2006 period.

3. Results

3.1. Field data

Figure 1 reports the various system responses to fertilization in terms of dry matter yield, N uptake, and soil total N content at the end of the experimental period. The analysis of variance showed significant differences in yields, N uptakes, and soil N content among the cropping systems ($P = 0.000$ in all cases), and among the fertilization managements ($P = 0.000$, $P = 0.000$ and $P = 0.012$, respectively). The yield and N uptake responses of the four cropping systems to fertilization management also showed differences (significant interaction of cropping system by fertilization management, $P = 0.004$ and $P = 0.000$, respectively) as opposed to a lack of observed interaction in soil N content ($P = 0.156$). Significant differences will be detailed and discussed hereafter, while presenting results of agronomic importance.

Yields plateaued at c. 200 kg ha^{-1} of N supplied as urea in Mg, Ms, and Ml, whereas Mr showed an increase above this fertilization level. Maize as a single crop produced more total biomass when crop residues (stalks, cobs and bracts) were returned to the soil (Mg, 24.2 t ha^{-1}) than when they were removed (Ms, 22.9 t ha^{-1}). The double-cropping system maize for silage - Italian ryegrass (Mr, 24.5 t ha^{-1}) as a two-crop sum achieved the same high biomass production levels as Mg. The average DM yield of the maize for silage-grass ley rotation (Ml) was 17% lower than that of single crop maize for silage (Ms), and 23% lower than Mr. In general, the organic fertilizers performed similarly to urea.

The crop N uptake is a more sensitive indicator than yield of crop nutrient status (Hermann and Taube, 2005). Given a luxury consumption, it never reached a maximum in the tested range of supply, except in Mg. When the entire plant was considered it was higher in Mg than in the other treatments (247 kg ha^{-1} vs 242 kg ha^{-1} in Ml, 237 kg ha^{-1} in Mr and 227 kg ha^{-1} in Ms, as an average of all fertilization types and levels). Highly-fertilized Ms and Mr were capable of 270-280 kg of N uptake that was removed as yield. The maize phase of Ml (292 kg ha^{-1} in U400) displayed the highest average value while the grass ley in this system partially compensated for a lower biomass yield with a higher N concentration than maize, resulting in a 20-50 kg ha^{-1} difference in N removal. We attributed the high N uptake of the Ml system when under-fertilized (0N, in particular) to an extra N-fixation by white clover that developed spontaneously in the sward (Grignani et al., 2007). Fertilization managements SHigh, FHigh, and U400 performed best (they ensured 254, 254, and 252 kg ha^{-1} of N uptake, respectively). In most situations, crops utilized organic fertilizers as well as or even better than urea (such as Ml at High dose, and Mr at both low and high doses).

The average N uptake in the 0N plot of the Mg, Ms, and Mr cropping systems was c. 130 kg ha^{-1} of N, or 2.4% of total soil N. This is consistent with the yearly mineralization rate of 2% reported by Bertora et al. (2009) for this soil. After 14 years without any fertilization, the N uptake of the control plots was low, but not decreasing (data not shown) which demonstrated that stable soil organic matter mineralization could still supply the crop.

The total N content of the soil in the 0-30 cm layer, measured at the end of the experimental period, was higher in Mg (5.7 t ha^{-1}) relative to the other systems, which shared similar values (5.2 t ha^{-1}, on average). The soil N content response to N fertilization as urea or to the absence of fertilization, was null, which suggests that mineral fertilization neither stimulated nor compensated the mineralization of the soil organic N. Slurry and farmyard manure additions increased soil N content by 13-33%; only manure showed a dose effect (FLow attained +17% and FHigh attained +33% of the average soil N content of treatments without organic fertilizers).

3.2. Indicators of N use efficiency and impact

Comparison among the cropping systems and among the three fertilizer types supplied in differing amounts is facilitated when N use efficiency indicators are calculated (Fig. 2). We relied on four calculated indicators to confirm our results of N use efficiency: R/F ratio, AR ratio, Surplus, and the SSyB indicator. The definition implications, as well as findings, are discussed below.

The R/F ratio, calculated using fertilizer and crop data (crop N removal), formulates the fraction of fertilizer that is allocated to harvest and is generally called 'N recovery.' It has a value of 1.0 when the amount of supplied N is equal to that removed at harvest. A value greater than 1.0 would indicate that another source, such as soil reserves, was exploited. In this experiment the indicator showed all cropping systems responded similarly to N fertilization, with lower values in Mg due to only partial plant harvest. R/F was equal to 1.0 at 174 kg ha^{-1} of N supply in Mg, and at 250-260 kg ha^{-1} in Ms, Mr, and Ml. At 400 kg ha^{-1} of supply, we observed the lowest values, which were in the range of 0.67-0.70 (0.45 in the case of Mg). The crop utilized both slurry and farmyard manure to the same extent as urea.

The AR ratio (Apparent Recovery) uses additional soil information (organic matter mineralization as estimated by the crop N removal in the 0N plot) to indicate the N use efficiency of fertilizers. 'Apparent' refers to the assumption that N uptake derived from the soil is not affected by N input (see Ten Berge at al., 2007). It is widely used to account for soil mineralization in the fertilization balance. AR highlighted a better performance by Mr and Ml relative to Ms and Mg; it decreased linearly as N fertilization increased from c. 0.8 to c. 0.4 (0.42 to 0.21 in Mg). If AR were calculated using the whole plant N uptake instead of yield N removal, values for Mg would be in the ±10% range of those for Ms. When maize straw was removed (Ms, Mr, and Ml), the AR indicator made evident some differences among fertilizers. For example, the efficiency of urea was higher or equal to that of organic fertilizers at low supply amounts, as opposed to organic fertilizers that released N slowly and exerted a better crop supply capacity when applied at amounts greater than 300 kg ha^{-1}.

Surplus represents a balance at the soil surface of fertilizer, crop, and atmospheric depositions. It is widely used as an indicator of potential losses and consequent threats to environmental quality (see the review by Öborn et al., 2003), although it fails to account for possible soil stock changes. A negative value indicates that the crop has utilized external sources of N, such as soil N. We found that fertilization linearly enhanced Surplus up to 148-157 kg ha^{-1} of N (248 in Mg) at the highest N supply. The slope was steeper at doses greater than 200 kg ha^{-1}. Slurry performed well and ensured a lower surplus, especially in the Mr system.

Third, the SSyB indicator estimated total losses from denitrification and leaching below the considered soil depth. Fertilizer, crop, soil, atmospheric depositions, and NH_3 volatilization data comprise this indicator. A negative SSyB indicates that the crop is exploiting some N from external sources, such as soil horizons beneath the one considered (0-30 cm in this study), or N fixation in the 0N plots of the Ml system. Given that the SSyB accounts for any soil stock change over time, its absolute value also depends on the soil N status at study start. The SSyB summed up to 180-227 kg ha^{-1} yr^{-1} in U400 plots in all cropping systems, which indicated that remarkable losses occurred regardless of crop removal or soil cover duration. Despite an average Surplus difference of 67 kg ha^{-1}, the SSyB of Mg fertilized with urea was only 21 kg higher than that of Ms, suggesting that changes in soil N partially compensated for the surface balance. This made evident that the soil partially retained urea-N in the presence of maize straw. The SSyB of plots treated with slurry or farmyard manure was remarkably smaller than that of plots that received urea; in fact, they were even negative at low amounts of supply. SSyB magnified the differences between cropping systems. The maximum observed values were 133 kg ha^{-1} in Mg and 71, 51, and 44 kg ha^{-1} in Ms, Ml, and Mr, respectively. The slope of the SSyB response to increasing slurry and manure supply was less steep than that of urea, which suggested that organic fertilization was mediated by the soil-storing capacity. Only in Ml did high doses of farmyard manure further reduce losses with respect to slurry.

The fourth indicator used in this study, Ko, expresses the fraction of available N in organic fertilizers. Figure 3 reports how Ko varies as a function of the amount of N supplied as total fertilizer (organic + urea). The Ms, Mr, and Ml systems and both types of organic fertilizers were pooled to draw one interpolation line on the graph. As it was calculated using N removal, values for Mg were substantially smaller than those of the other systems and cannot be compared directly. Ko was greater than 1 when sources of N other than fertilization and atmospheric depositions were utilized by the crop (N fixation, soil N). The fraction of slurry- or manure-N made available to the crop was 1.0 at 215 kg ha^{-1} of N, which decreased as N supply increased to 0.60 at 350 kg of total N supply.

The calculation described above is key in the agri-environmental legislation of some European countries. The regional and national framework legislation that acknowledged the Nitrates Directive (currently D.M. 7 April 2006) are being modified to set permissible N supply amounts for each crop and a target Ko value at the farm level that will probably be 0.40 for farmyard manure, 0.50 for bovine slurry, and 0.60 for pig slurry. The experimental values reported here highlight that these goals can be achieved, and even exceeded at 250 kg ha^{-1} of organic-N supply. A similar approach used in the Netherlands (Schröder and Neeteson (2008) is the Fertilizer Replacement Value of Manure (NFRV). It can be demonstrated that at a given N removal, Ko and NRFV are numerically equal. As a comparison, 0.80 and 0.60 are the fertilizer replacement values for slurry and farmyard manure in the Dutch legislation.

Different fertilizers are best compared if N supply values are standardized such as if a value of 270 kg ha^{-1} were to represent 170 kg ha^{-1} of manure-derived N plus 100 kg ha^{-1} of mineral fertilizers (Tab. 2). The R/F, AR, and Surplus indicators showed an overall equivalence across urea, slurry, and manure, whereas SSyB indicated a minor impact for managements that include organic fertilizers.

3.3. Soil mineral N concentrations

The NO_3-N concentration in the 0-50 cm soil layer ranged from 0 to 51 mg kg^{-1} of dry soil. The temporal variations (data not shown) were remarkable in all tested treatments. Average values reported in Table 3, averaged by time and replicate, show a linear relationship to fertilization amount (R^2 = 0.38), Surplus (R^2 = 0.41) and SSyB (R^2 = 0.67).

The residual NO_3-N soil mineral N content in the 0-50 cm layer at maize harvest (same Tab. 3) was also linearly related to fertilization ($R^2 = 0.61$), Surplus ($R^2 = 0.71$) and SSyB ($R^2 = 0.70$).

The NO_3-N concentration in the soil solution extracted by porous cups at a depth of 100 cm ranged from 0 to 91 mg l^{-1}. Temporal trends (data not shown) showed that the soil solution concentration was a more sensitive indicator of treatment differentiation than soil mineral N. The average values reported in Table 3 were also linearly related to fertilization ($R^2 = 0.48$), Surplus ($R^2 = 0.51$), and SSyB ($R^2 = 0.68$). We found the nitrate-N concentration at 100 cm exceeded the threshold limit of 11.3 mg l^{-1} set by the European Union for drinkable water in more than 50% of samples in nearly all fertilized treatments. In general, Mr and Ml systems showed lower soil and soil solution N concentrations than Ms and Mg.

3.4. N leaching

Simulation model Daisy (Abrahamsen and Hansen, 2000) predicted N transformations in all tested cropping systems at the typical fertilization level of 270 kg ha^{-1} of N, applied as urea, slurry, or farmyard manure. The model predictions, reported in Table 4, agreed with the experimental results and calculations for Surplus ($R^2 = 0.85$, slope = 1.14, intercept = -25.3; RMSE = 82 kg ha^{-1}) and SSyB at 270 kg ha^{-1} of N supply ($R^2 = 0.74$, slope = 0.64, intercept = 17.4; RMSE = 76 kg ha^{-1}).

The simulated water drainage below the soil profile averaged c.130 mm, which is 17% of rainfall in the Mg and Ms systems. Drainage was reduced by 20% in Ml consequent to higher evapotranspiration from prolonged soil cover. The most drainage occurred during December-January and June-July as due to autumn and spring intense rainfall (data not shown).

NH_3 volatilization losses ranged between 11 and 23 kg ha^{-1} yr^{-1}. Denitrification was of similar magnitude (15-31 kg ha^{-1} yr^{-1}).

Simulated leaching from below the soil profile ranged from 0 to 169 kg ha^{-1} yr^{-1}, with high cross-year variability. Despite the magnitude of N flows, average annual leaching losses were not necessarily high, and were generally below 40 kg of N ha^{-1}. Leaching in Ms and Mg was higher than in Mr, and higher in urea-treated plots than in slurried and manured ones. The mineral N concentration of water drained below the soil profile ranged from 6 to 48 mg l^{-1}; in most cases, the values were high above the EU threshold limit for drinking water. If drainage were 130 mm, and respecting the N concentration target concentration limit, then deep percolation should be limited to 15 kg ha^{-1} of N.

Leaching was linearly related to SSyB ($R^2 = 0.87$, $P = 0.000$). The regression showed 52% of SSyB leached below the soil profile. Conversely, leaching did not correlate to Surplus, which is a contrary finding to work done in the Netherlands (Van Beek et al., 2003; Schröeder et al., 2007).

4. Discussion

Yield and N uptake of well-fertilized maize under these experimental conditions were high, up to 33.3 t ha^{-1} of dry matter and 367 kg ha^{-1} of N. These yields and N uptakes are among the highest recorded in Europe (Rüegg et al., 1998; Schröder et al., 1998; Gabrielle et al., 2005; Montemurro et al., 2006; Colomb et al., 2007), USA (Yamoah et al., 1998; Bakhsh et al., 2005) and Australia (Muchow, 1998). However, in the fertile Po Plain, they are common not only under the controlled conditions of experimental trials (Onofrii et al., 1993; Giardini, 2004; Ersaf, 2009), but also on ordinary farms. For instance, Tabacco and Borreani (2009) observed N uptake values between 224 and 314 kg ha^{-1} in a study of 183 farms in Piemonte. The double-cropping system yield and N uptake in this study was not as high as that reported in other Italian (Onofrii et al., 1993) and Portuguese (Trindade et al., 2008) studies; in those instances, maize produced 10-20% more biomass. The yields and uptakes of grass leys were also similar to those obtained in local farm conditions. High growth rates and a long growing season (up to 270 days) are expected for grass in this environment when water is not restricted (Grignani, 1990; Cavallero and Ciotti, 1991; Grignani, 1991; Onofrii et al., 1993; Grignani et al., 2003; Giardini, 2004). The experimental site is representative of a large area of the northwest Po Plain, if not larger than the 255,000 ha wide surface that Bassanino et al. (2011) outlined in the Piemonte region.

The tested cropping systems differed in terms of N use efficiency as revealed by several indicators. On the basis of these results, we evaluated each system as an alternative to maize grain monoculture, the most diffuse crop in the western Po Plain (ISTAT, 2000), at the standard fertilization level of 270 kg ha^{-1} of N.

4.1. The standard situation: maize for grain

Fertilization with 200-250 kg ha^{-1} of N ensured the highest grain yields in this trial. As Figure 1 shows, a further increase in the amount supplied had no yield effects. The yield and uptake associated with the whole plant in Mg systems were higher than those of the other systems, apparently owing to a higher availability of N from recycled crop residue. Data on soil and soil solution NO_3-N concentration corroborated this result as it showed a moderate tendency to be higher in Mg than in Ms systems, and it contained a greater percentage of cases that exceeded the threshold limit for NO_3 concentration (Tab. 3). Straw is easily mineralizable organic matter that is mostly decomposed within one year (Bertora et al., 2009). In fact, Monaco et al. (2008) reported that the Potentially Mineralizable Nitrogen to total N ratio (PMN/total N) was equal to 2.10% in the MgU200 system and 0.78% in the MsU200. In this experiment the limited portion of N in straw that was retained by the soil was sufficient to increase the stable organic pool (Fig. 1). Incorporation of a material with a high C to N ratio was of particular benefit in treatments fertilized with urea, as it allowed a more efficient incorporation in the SOM of mineral N released from urea, as indicated by the high soil total N content of Mg fertilized with urea *versus* the corresponding Ms treatments (Fig. 1).

As all indicators showed, the N use efficiency of Mg was apparently the lowest among the cropping systems because of the limited N removal. At a fertilization level of 270 kg ha^{-1}, the R/F indicator was in the range of 0.65-0.67 and AR was 0.30-0.32, Surplus was 115-121 kg ha^{-1} and Ko was

0.29-0.32 (Tab. 2). Total potential losses were moderate when organic fertilizers were supplied, according to SSyB calculations (72 and 77 kg ha^{-1}, respectively). Average leaching was only 12-29 kg in slurried and manured systems, but the mean concentration of deep percolating water from the MgS270 treatment was above the permissible level (Tab. 4).

The total amount of fertilizer supplied to Mg systems could be reduced to limit leaching and other potential losses. Borin et al. (1997), Morari, and Giupponi (1997) reported that reduced fertilization (250 kg ha^{-1}) was highly effective to reducing the N impact on groundwater quality compared to high-input management (360 kg ha^{-1}). Tarkalson et al. (2006) observed the same in the USA at very high total N fertilization manure supplies.

Optimal fertilization can be soil surface balance based. The Surplus in Mg was null at 115 kg ha^{-1}. If fertilization were lowered so as to produce no Surplus, yields would fall by 14% at 270 kg ha^{-1} of N supply, and the SSyB would be -29 kg ha^{-1} in slurried and manured systems, suggesting a soil stock depletion. Surplus can be reduced to a permissible level and some regions of Northern Italy have defined a maximum allowable surplus at the field scale calculated from more complex balance formulas than the one used here, such as the 30 kg ha^{-1} set in Emilia Romagna (Regione Emilia Romagna, 2007) and the 60 kg ha^{-1} set in Veneto (Regione Veneto, 2008). Some countries, such as the Netherlands, have also set imbalance limits at the farm scale (100 kg ha^{-1} in 2008, van Keulen et al., 2000). In this trial, a Surplus of 60 kg ha^{-1} of N would be reached at 213 kg ha^{-1} of N supply and would imply a SSyB of 35 kg ha^{-1} in slurried and manured systems without a decrease in yield.

4.2. Option 1: harvest of the total plant

If one were to convert an Mg system to an Ms system, the N use efficiency would improve because of higher N removal (Tab. 2). R/F would increase to 0.87-0.93, AR to 0.41-0.47, and Ko would be 0.64-0.72. Surplus would be reduced by 60-71 kg ha^{-1} of N, and SSyB indicator shows that potential losses would also be reduced by 26-40 kg. Nitrogen leaching would fall 10-25% from that in Mg as simulated losses show in Table 4; the leachate concentration would also be reduced by 1-5 mg l^{-1}. In this instance, the environmental advantage of higher N removal would be partially counterbalanced by a lower retention in the soil as SOM.

The option of removing the entire maize biomass should be considered carefully because part of the straw, 6% according to Bertora et al. (2009), is retained in the soil and increases the SOM content with beneficial effects on general soil fertility (Dick, 1992). Soil analyses have shown that during the 14 years of the trial, an extra-accumulation of 618 kg ha^{-1} yr^{-1} of SOM was achieved in Mg relative to Ms treatments, in the ploughed layer. If straw were removed from the soil, the accumulation of organic matter and carbon sequestration would be reduced. If calculated for the entire Piemonte plain (592,973 ha, of which 25.5% is maize for grain; Bassanino et al., 2010), then the annual reduction would be 54,130 t of C.

Mg could be converted to an Ms system also if straw were removed from the field after grain harvest. The only difference between Mg with straw removal and Ms is the harvest date; it is delayed about one month if grain is produced. Silage maize was harvested at physiological maturity in this trial, after which dry matter no longer accumulated and grain humidity changed from 45-50% to 15-25% (Grignani, unpublished data).

4.3. Option 2: shift to a double-cropping system

The Mr system as a sum of the two crops out-yielded Ms, and its high potentiality was more evident at high fertilization amounts and when organic fertilizers were used. This system exerted a high capacity for extracting N from the soil, and high N use efficiency indicators showed a better performance relative to Ms. Indicators showed the following values: R/F was 0.93 or higher, AR ranged between 0.51 to 0.60, and Surplus was never above 46 kg ha^{-1}. The SSyB was also very low and Ko was high (0.74-0.88) in manure and slurry systems. This suggested a better synchronization between late-sown maize requirements and the N released by late-supplied slurry and manure (as better detailed by Grignani et al., 2007). Conversely, urea was utilized as much as in the Ms system, notwithstanding the longer soil cover.

Grass winter cover and enhanced fertilization efficiency effectively reduced the amount of N leached below the soil profile by 25-40% at the reference value of 270 kg of supply (Tab. 4), relative to Ms. On the contrary, Borin et al. (1997), Morari, and Giupponi (1997) reported that Italian ryegrass did not reduce N leaching. However, in that case, slurry was distributed partly in spring when maize was sown, and partly in autumn when grass was sown, whereas slurry was entirely supplied to the maize in this trial. Rüegg et al. (1998) reported that a maize-rye double-cropping system halved the residual mineral N soil content in Switzerland compared to single crop maize.

The root and residues of grass also caused SOM to increase by c. 255 kg ha^{-1} yr^{-1} compared to Ms treatments, but this never led to statistically significant differences, even after 14 years.

4.4. Option 3: rotation with grass ley

Rotation between full-plant harvested maize and a temporary (3-4 years) grass ley produced less total biomass than did other cropping systems, but was capable of very high N uptakes, as much as 240-270 kg ha^{-1} yr^{-1} of N (Fig. 1). Our results suggest a higher efficiency of farmyard manure than slurry on the ley, which contradicts reports by other authors (Eriksen et al., 2004).

The indicators reported in Table 2 suggest that the N use efficiency of the Ml system relative to the other systems was high when farmyard manure was supplied, intermediate between Ms and Mr with the application of slurry, and low when urea was supplied. The SSyB of Ml was similar to the corresponding maize in monoculture (Ms) when urea or slurry were supplied, and 39 kg ha^{-1} lower when manure was used. The rotation ensured a reduction in N leaching relative to Ms and Mg only when fertilized with urea (Tab. 4).

The rotation did not seem a viable option to reduce the negative effects of intensively-managed maize to the environment, contrary to findings by Nevens and Reheul (2002), Kayser et al. (2008). Also Schröder et al. (2007) reported that cut grassland in the Netherlands could have a low impact on the groundwater quality even when supplied with large manure amounts (340 kg ha^{-1} of N).

The soil N build-up that is normally observed in grass leys was probably hindered by an enhanced mineralization at grass ploughing (Whitehead, 1995; Kayser et al., 2008), and resulted in a final soil N content similar to that measured in the continuous arable system (Fig. 1). However, no peak mineral N concentration was observed in the soil after ploughing-in the ley (data not shown).

The ley phase did not produce the expected positive effects on maize. When compared with Ms in the corresponding years, maize benefited slightly from rotation as shown in a 5% yield increase and a 6% N uptake increase (ANOVA results: $P = 0.006$ and $P = 0.028$, respectively), when fertilized with urea, and not when supplied with organic fertilizers. Nevens and Reheul (2002) also reported an increase in the yield of rotational maize fertilized with urea in a study conducted in Belgium.

4.5. Option 4: change fertilizer type

Efficiency indicators that analyze soil surface information (R/F and Surplus) highlighted the fact that organic fertilizers made N available to crops to the same extent as urea. Conversely, efficiency indicators that include soil factors, such as AR and SSyB, showed that organic fertilizers were better retained in the soil than was urea. The slope of the response of SSyB to increasing amounts of supply was also less steep than that of urea, thus indicating a lower proportion of losses of N derived from organic rather than from mineral fertilizers (Fig. 2).

Slurry and farmyard manure released N similarly to the crop, but they differed in the way they were retained in the soil. Manure increased the SOM content to a greater extent than slurry did. The N use efficiency of slurry was generally equal or slightly higher than that of manure. Farmyard manure was the only fertilizer type that preserved the SOM content and ensured a low level of leaching.

An N use efficiency of organic fertilizer similar to that of urea is not commonly reported in the literature (Duthion, 1981), but there are three likely reasons. The first is that organic fertilizer distribution was repeated for several years as is common on livestock farms. Consequently, not only easily decomposable compounds, but also recalcitrant fractions were mineralized. Monaco et al.

(2010b) have demonstrated that most of the beneficial effects of using manure relies on past fertilization supply, and that fresh organic fertilization does not affect net N mineralization rates. Second, organic fertilizers were added as top dressing with 100 kg ha^{-1} of urea-N supplied as local farmers normally would. Therefore, the results presented here are not effects of organic fertilizers alone, but rather those of a fertilization practice that includes both types of N supply. Finally, the practice of treating plots with urea as described in this trial was inefficient since most of N was supplied at sowing. However, other authors have reported that the N use efficiency of organic fertilizers can be high. Chang and Janzen (1996) found that 56% of farmyard manure-N was available over time in a long-term experiment in Canada, whereas Schröder et al. (2005) reported that the AR of injected cattle slurry-N after eight years of additions in the Netherlands was 80%. Simulated leaching (Tab. 4) suggested that organic fertilizers could damage groundwater quality to a minor extent if compared to urea. In particular, this reduction was 30-60% when slurry was used, and 50-80% when farmyard manure was used. This also directly opposes reports by other authors (e.g. Borin et al., 1997; Morari and Giupponi, 1997; Edmeades, 2003; Thomsen, 2005; Bakhsh et al., 2005), who found larger leaching losses in slurry- than in urea-treated maize plots. However, N leaching was of the same order of magnitude as that reported in the eastern Po Plain by Mantovi et al. (2006) who registered leaching losses of 62 kg ha^{-1} yr^{-1} in maize treated with pig slurry, and Morari and Giupponi (1997) who reported that 85 kg ha^{-1} yr^{-1} were leached from maize-Italian ryegrass supplied with slurry.

As N use efficiency indicators and simulated leaching have not shown greater N losses in well managed organic fertilizers than urea (i.e. distributed before sowing and soon incorporated), any limitation in the permitted amount of slurry and manure probably would not diminish the impact of N fertilization on groundwater quality as environmental effects are determined by the total supply, regardless of its source (as also stated by Schröder et al., 2007).

5. Conclusions

Maize is and will certainly remain the main crop in the Po Plain regardless of any present or future legislation to limit its management practices because it simply performs better than all other crops in its soil and climate conditions. The challenge for environmental agronomists is to direct agri-environmental policy adoption through farm collaboration and dissemination of viable practices to reduce the negative impact of intensive cropping systems.

Our analysis showed that the N impact of maize-based cropping systems is reduced (i) when the whole plant is harvested, (ii) when a secondary winter crop is sown, and (iii) when organic fertilizers are used and well managed. The total fertilization amount was shown to be important in determining losses; any fertilizer reduction would limit the impact of maize and improve the efficiency of N. A set of N use efficiency indicators has been presented to facilitate comparisons with other trials and with the various approaches utilized in national and regional legislation to implement EU Directives (van Dijk and Ten Berge, 2009; Bouma, 2011). As Schröder et al. (2004) also declared, a strong need exists for harmonizing environmental policy approaches across Europe.

Our work focused on N and disregarded other environmental issues. Phosphorous load, NH_3 volatilization, and greenhouse gas emissions need careful consideration when high amounts of organic fertilizers are applied. Further experiments are needed to explore options beyond those outlined here, including top-dressing with organic fertilizers, slurry fertigation, and slurry soil injection.

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Tables

Table 1. Average total N supply (kg ha^{-1}) to the different cropping systems during 1993-2006 as the sum of organic and mineral fertilization supplied as urea (100 kg N ha^{-1} at ridging, every year, in all fertilized treatments).

	0N	U100	U200	U300	U400	SLow	SHigh	FLow	FHigh
Mg, Ms	0	100	200	300	400	207	313	232	364
Mr	0	100	200	300	400	205	310	231	361
Ml	0	100	200	300	400	192	282	216	331

Mg, maize for grain production; Ms, maize for silage; Mr, double annual crop rotation maize for silage-Italian ryegrass; Ml, grass ley-maize for silage rotation.

0N, unfertilized control; U100, U200, U300 and U400, N fertilization using urea at 100, 200, 300 and 400 kg N ha^{-1}, respectively; SLow and SHigh, fertilization with bovine slurry at low and high level, respectively; FLow and FHigh, fertilization with farmyard manure at low and high level, respectively.

Table 2. N use efficiency indicators of the different cropping systems at 270 kg N ha^{-1} of total N supply, obtained through linear interpolation between measured values. The indicators are defined in Section 2.4.

	R/F			AR			Surplus (kg ha^{-1})			SSyB (kg ha^{-1})			Ko	
	U	S	F	U	S	F	U	S	F	U	S	F	S	F
Mg270	0.67	0.67	0.65	0.32	0.32	0.30	117	115	121	121	72	77	0.32	0.29
Ms270	0.93	0.92	0.87	0.47	0.41	0.41	46	48	62	95	35	37	0.72	0.64
Mr270	0.93	1.02	0.94	0.51	0.60	0.52	46	21	44	105	-3	7	0.88	0.74
Ml270	0.89	0.97	0.97	0.43	0.51	0.51	56	34	35	96	44	-2	0.80	0.79

Mg270, Ms270, Mr270 and Ml270, maize for grain production, maize for silage, double annual crop rotation maize for silage-Italian ryegrass, and grass ley-maize for silage rotation fertilised at a standard level of 270 kg N ha^{-1}.

R/F, removal to fertilizer ratio; AR, Apparent Recovery; Surplus, deposition+fertilization-removal N balance; SSyB, Soil System Balance. U = urea, S = slurry+urea, F = farmyard manure+urea.

Table 3. Nitrate-N concentration in the 0-50 cm deep soil layer, residual NO_3-N at harvest in the 0-50 cm layer, and NO_3-N concentration in the soil solution at 100 cm depth. Summary of two sampling campaigns: 1 = from August 1993 to April 1996, 2 = from April 2002 to June 2003.

	Soil NO_3-N in the 0-50 cm soil layer				Residual N in the 0-50 cm soil layer			NO_3-N in the soil solution at 100 cm				
Treatment	Avg. (mg kg^{-1})	SD	n	Campaign	Avg. (kg ha^{-1})	n	Campaign	Avg. (mg l^{-1})	SD	n	Campaign	Frequency > 11.3 mg l^{-1} (%)
Mg0	3.0	2.2	52	1	11.5	4	1	5.1	5.0	43	1	14
MgU300	n.d.	-	-	-	n.d.	-		20.5	8.1	26	2	100
MgSLow	5.7	3.8	55	1	21.6	4		15.5	8.8	69	1,2	65
MgSHigh	n.d.	-	-	-	n.d.	-		21.2	8.6	26	2	88
MgFHigh	10.0	8.4	43	2	57.9	2		21.3	9.0	25	2	84
Ms0	2.8	1.7	87	1,2	8.0	6		8.8	9.2	43	1	28
MsU300	14.8	12.4	36	2	37.9	2		30.9	18.7	25	2	92
MsSLow	5.4	3.7	53	1	30.2	4		15.2	14.2	68	1,2	47
MsSHigh	7.1	6.3	93	1,2	27.3	6		24.0	15.6	69	1,2	74
MsFLow	3.7	2.2	54	1	13.6	4		13.1	8.3	69	1,2	51
MsFHigh	n.d.	-	-	-	n.d.	-		10.4	6.1	25	2	36
Mr0	2.0	1.5	51	1	12.8	4		2.5	2.9	42	1	2
MrSLow	4.2	4.0	51	1	27.9	4		7.4	9.4	42	1	21
MrSHigh	1.6	1.9	34	2	26.2	2		9.1	19.3	22	2	18
Ml0	1.7	1.8	47	1	7.1	3		2.3	5.2	45	1	2
MlSLow	2.1	1.7	48	1	9.4	3		2.6	5.1	45	1	9
MlSHigh	12.1	10.4	43	2	45.2	2		23.6	16.5	26	2	73

SD, standard deviation; see Table 1 for an explanation of treatments.

Table 4. Simulated SSyB, water drainage, N leaching below the soil profile (2.50 m) and flow-averaged N concentration in the different cropping systems at 270 kg ha^{-1} of N supply.

Treatment	SSyB (kg ha^{-1} yr^{-1})	Drainage (mm yr^{-1})	N leaching (kg ha^{-1} yr^{-1})	N concentration (mg l^{-1})
MgU270	129	131	63	48
MgS270	61	136	29	21
MgF270	47	132	12	9
MsU270	87	131	56	43
MsS270	31	136	22	16
MsF270	26	132	10	8
MrU270	65	125	33	26
MrS270	28	130	14	11
MrF270	26	127	8	6
MlU270	77	104	39	37
MlS270	33	108	27	25
MlF270	31	105	19	18

Figure captions

Figure 1. Yield, N uptake (average data 1993-2006), and soil N content in the 0-30 cm layer at the end of the experimental period (spring 2007), as a response to N fertilization (sum of mineral and organic). Bars are the standard error of between-years variability of each treatment.

Figure 2. Indicators of Nitrogen use efficiency and impact in response to the fertilization level (sum of mineral and organic) of the different types of N sources.

Figure 3. Fraction of available N of organic fertilizers, indicated by the Ko coefficient, as a function of the total N supply (organic + 100 kg of N as urea). S, slurry; F, farmyard manure; Mg, maize for grain production; Ms, maize for silage; Mr, double annual crop rotation maize for silage-Italian ryegrass; Ml, grass ley-maize for silage rotation.

Figures

Fig. 1.

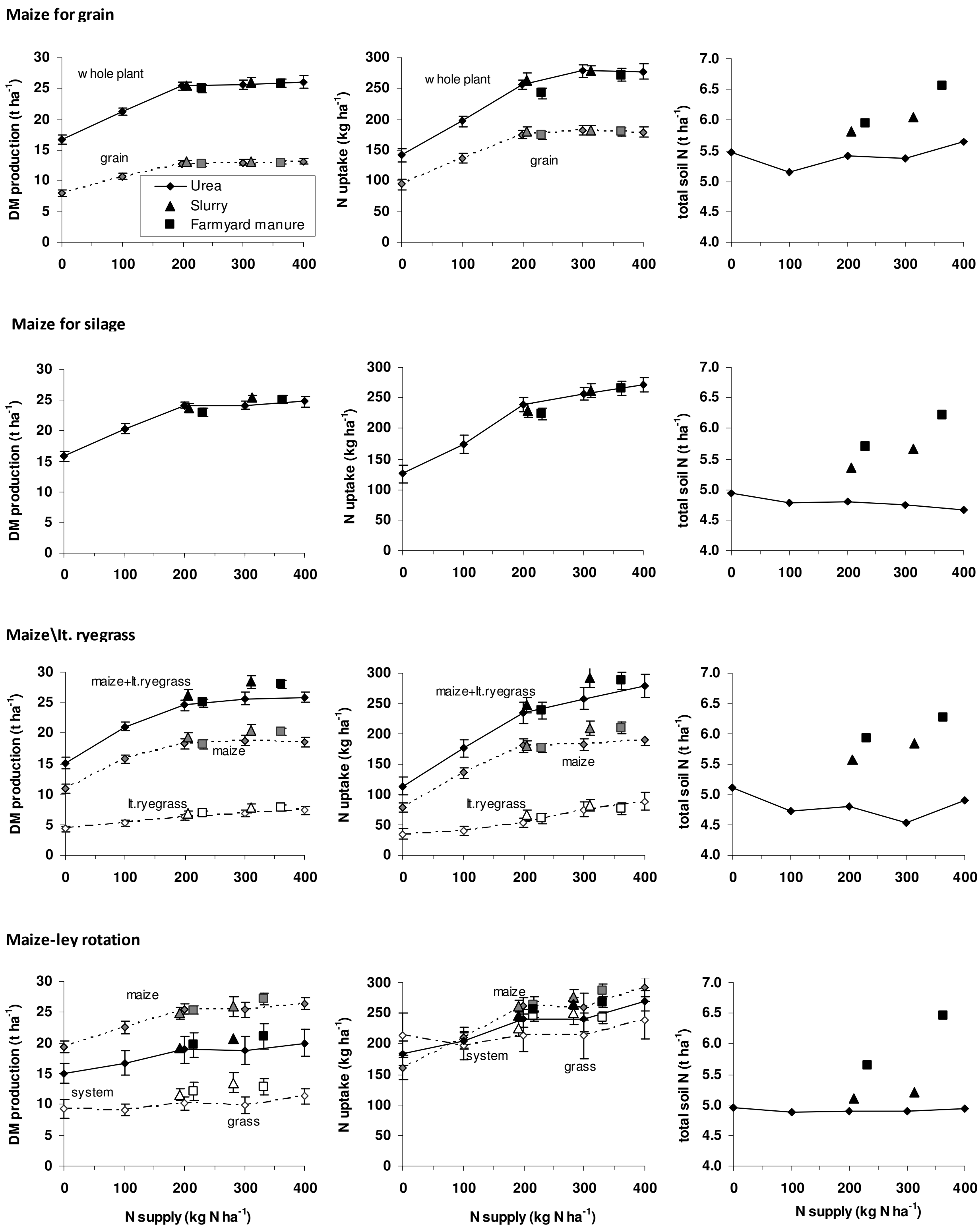
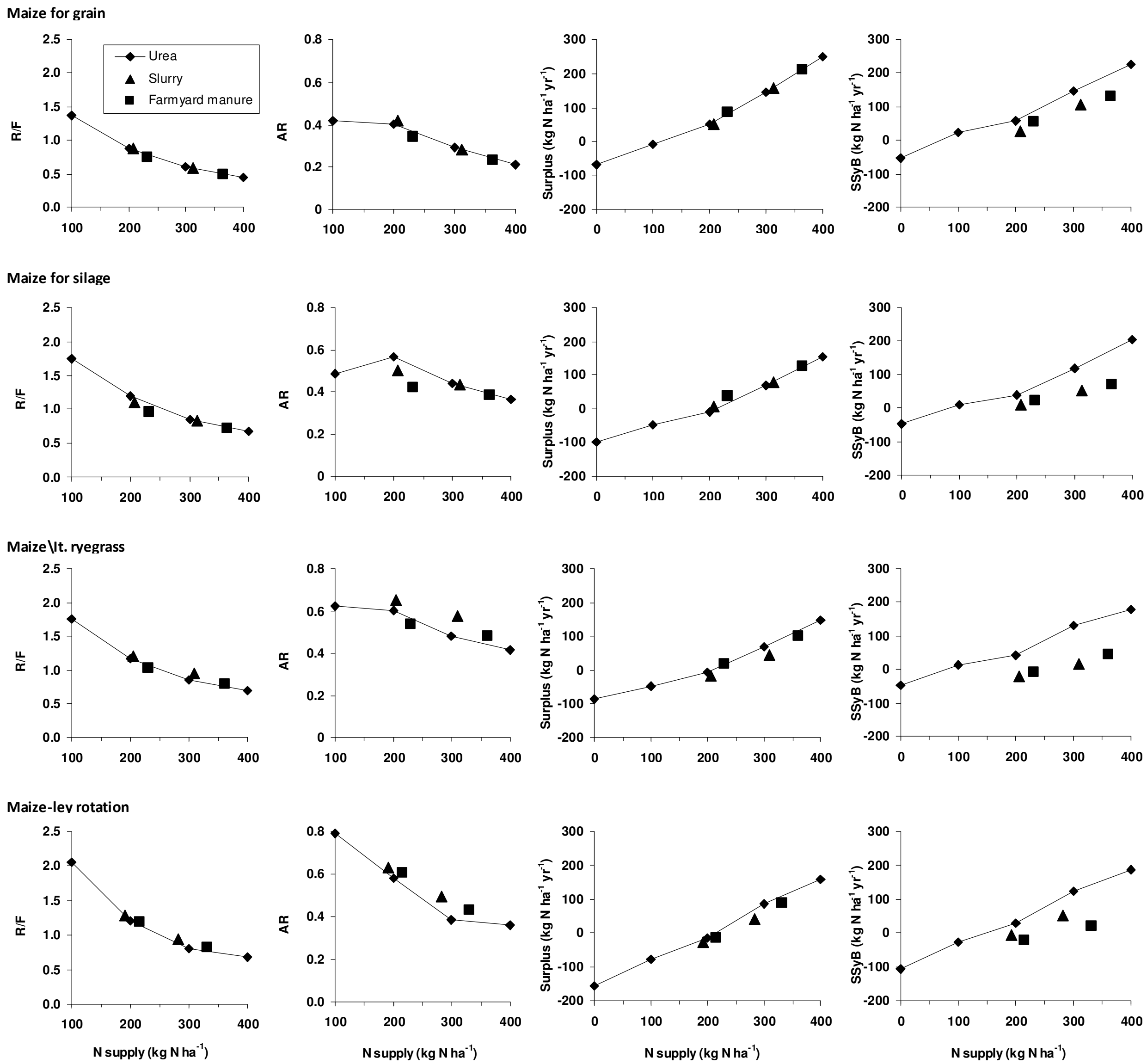
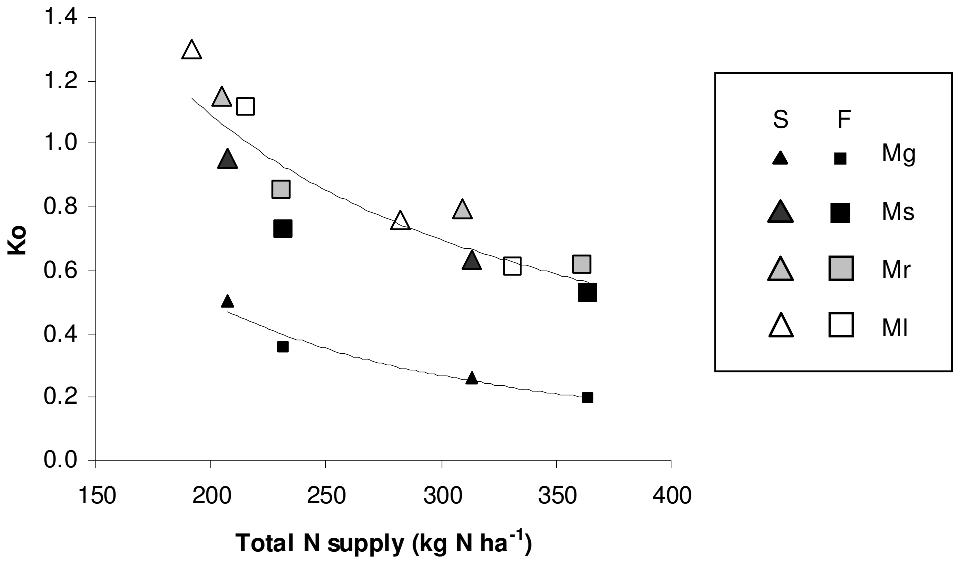


Fig. 2.



Maize for grain
Maize for silage
Maize\It. ryegrass
Maize-ley rotation
Urea
Slurry
Farmyard manure
R/F
AR
Surplus (kg N ha-1 yr-1)
SSyB (kg N ha-1 yr-1)
N supply (kg N ha-1)

Fig. 3.



1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Ko
150
200
250
300
350
400
Total N supply (kg N ha-1)
S
F
Mg
Ms
Mr
Ml